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Partnering for Success

Role of Smallsats for ET retrievals:
Potential ~~and Limitations~~

Dr. Darrel Williams

Global Science & Technology, Inc. (GST)

2015 International Workshop on Evapotranspiration Mapping for Water Security

September 15-17 / The World Bank / Washington, DC

Outline of Talk

- **Importance of Landsat and impact of cloud cover on ability to acquire sufficient Earth observations – need many more assets in orbit**
- **Why investigate small satellite solutions? – much lower cost**
- **Chronology of events since mid-2010 when our Landsat Smallsat concept development activities were initiated**
  - **Goal has been to maintain current performance, but lower cost significantly**
- **Received '15 funding via NASA's Sustained Land Imaging program to evolve Smallsat compatible instrument designs**
  - **Specific to ET retrievals, Utah State University's Space Dynamics Lab's (SDL) Thermal Earth Resource Monitoring Instrument (THERMI) concept fulfills all Landsat 8 TIR performance requirements but at improved 60m spatial resolution**
- **Summary thoughts**
  - **Smallsat potential for reliable ET retrievals is high**; the predominant limitations are out dated perceptions and politics

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Importance of Landsat

NATIONAL PLAN FOR
CIVIL EARTH OBSERVATIONS

PRODUCT OF THE

Office of Science and Technology Policy
Executive Office of the President

July 2014

Annex I: 2012 EOA Results

This annex provides results for the 145 high-impact observation systems identified from the 362 observation systems assessed by the 13 SBA teams of approximately 300 Federal subject-matter experts. These 145 observation systems are listed in two tiers in the tables below. Impact is indicated with respect to each of the 13 societal themes (12 SBAs and reference measurements), as described in Section 2.2.

Table 1: Tier 1 High-Impact Observation Systems (Ranked Order)

Observation System (Ranked Order)	Agency	Ag&Frst	BioDiv	Climate	Disasters	Ecosys	Energy	HumanHlth	Ocn&Cstl	Space Wx	Trans	WaterRes	Wx	RefMeas
1. Global Positioning System (GPS) satellites	DOD/USAF													
2. Next Generation Weather Radar (NEXRAD)	DOC/NOAA								*					
3. Landsat satellite	DOI/USGS, NASA										*			
4. Geostationary Operational Environmental Satellite System (GOES-NOP)	DOC/NOAA			*		*								
5. National Agriculture Imagery Program (NAIP)	USDA/FSA													
6. Airborne LIDAR	DOC/NOAA, DOD/USACE, DOI/USGS, NSF													
7. Forest Inventory and Analysis (FIA)	USDA/USFS							*						

Impact: Contributes * | Moderate | High | Very High | Highest

Landsat ranked 3rd, only behind GPS and weather radar.

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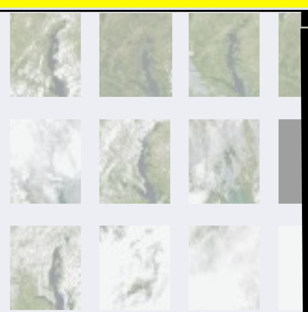
How often do we really need to observe?

An example assessment of daily cloud cover using MODIS "Landsat-sized chips" for growing season months – June, July, August & Sept in DC area.

ANSWER: FOR MOST VEGETATED REGIONS WE NEED DAILY REPEAT COVERAGE TO CREATE WEEKLY CLOUD-CLEARED DATA SETS!



Repeat Cycle	Reliable Clear Views
1 day	Weekly
2 days	Bi-weekly
4 days	Monthly
8 days	Seasonal (quarterly)
16 day	Annual (sometimes)

Journal article currently in review at Remote Sensing of Environment.

- Visual assessment of cloud cover in MODIS "Landsat sized" chips (see center column above)
- Each image assigned rank of 1 - 4 based on cloud cover in chip – then over an 8 yr period we assessed ability to create a cloud-free mosaic product if we had 1 day repeat coverage, 2 day repeat, and so on.

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Why Investigate Smallsat Solutions?

- **Spaceflight mission costs heavily driven by mass, volume & power**
- **Economic environment / budgets are stressed nationally / globally**
- **Complexity & cost of Earth obs missions have risen dramatically**
- **Sen. Barbara Mikulski, Chair, Senate Appropriations Committee:**

  "We need to see more Chevy-priced mission concepts, not just Cadillac-priced missions with uncapped cost growth" [April '10 SpaceNews article]

- **Technology evolution as demonstrated by smart phones, laptops, tablets needs to be embraced** (smaller size, much lower power demands, greater capability)
  - **Smallsats offer a pathway for quicker adoption of new technologies at significantly lower cost, while also providing insurance against crippling data gaps**

My Background and Chronology of Activities re: Developing Smallsat Solutions

- **35-yr NASA career, ~20 yrs as Landsat Project Scientist**
- **Realization that NASA New Millennium Program EarthObserver-1, a smallsat, still operational well beyond its 1 yr design life** (~14 yrs)
- **Transitioned from NASA to private sector (GST) in Feb ’10**
  - Wanted to ask questions, get candid answers w/o the sales hype
- **Conducted exhaustive review of existing low-cost Earth imagers and small satellite missions**
  - Always asking: **Does something reliable already exist that could, with the right adjustments, be morphed into a viable Landsat mission?**
- **Evolution of improved imaging capabilities by Surrey’s Disaster Monitoring Constellation (DMC) was noteworthy**
- **GST & Surrey US teamed and began to evolve a viable concept**
  - NASA’s Earth Venture-2 Announcement of Opportunity, issued in March ’11, sharpened our focus and sense of urgency
  - Developed fully compliant VNIR/SWIR solution; proposal submitted Sept ’11
    - did not include thermal imaging capability at that time

NASA Sustained Land Imaging Instrument Study Requirements

- **Jumping forward in time**
  - During the interim, we responded to Landsat related RFIs issued by USGS, NASA & OSTP
  - Added highly regarded thermal imaging capabilities of Space Dynamics Lab to our Team
- **Early '15, Team SST-US was one of six groups that competed for and received study money via NASAs Sustained Land Imaging (SLI) Office** to conduct a six month study to evolve small instrument conceptual designs, decisions and trades.
- **Primary intent of studies was to design much smaller instrument package(s) that could meet stringent Landsat 8 performance requirements** for both the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)
- **NASA provided Landsat 8 OLI and TIRS requirements spread-sheets to SLI selectees, who were required to:**
  - Develop radiometric math models and conduct detailed analyses including SNR, dynamic range, absolute radiometric uncertainty / stability, pixel-to-pixel uniformity, optical design
  - Perform analyses including relative edge response, geometric and spatial error budget
  - Perform stray light analyses for both diffused/scattered and ghosting/coherent stray light
  - Document relative spectral and out of band responses
  - Conduct end of life degradation performance analyses

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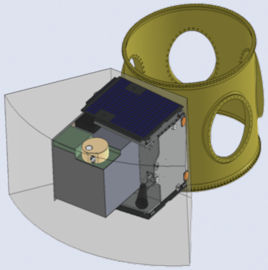
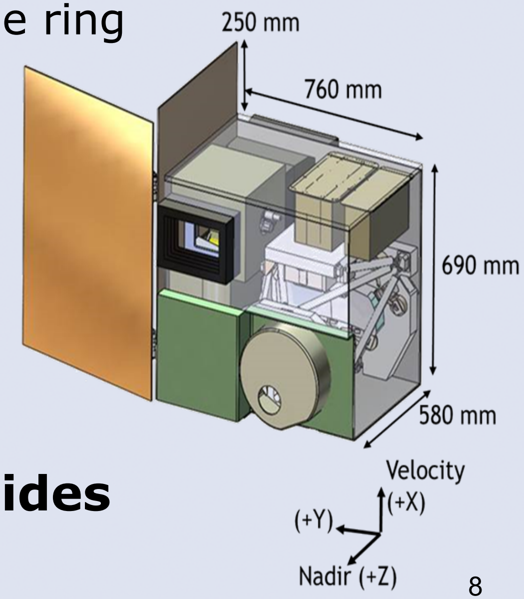
Team SST-US SLI Solution

- **Team SST-US started with two existing instrument concepts**
  - Surrey's TrueColor and SDL's TIR imager
- **Investigated combining the telescopes but concluded that two separate telescopes / imagers were needed to provide desired Landsat 8 performance**
- **Our final VNIR/SWIR and TIR instrument designs**
  - **Meet all Landsat 8 performance requirements**
  - **Meet Smallsat accommodation** (on an SSTL-300 bus) **and ESPA Grande** (secondary) **launch requirement**
  - Instruments are shown on an SSTL-300 bus/ESPA Grande ring



- **Est. cost for whole mission provided to NASA**
  - Expected to be **~1/4 cost of Landsat 8**
  - VNIR/SWIR instrument expected to be ~1/4 cost of OLI
  - SDLs TIR instrument expected to <1/4 cost of L8 TIRS



- **Details of SDL's THERMI imager on following slides**

Space Dynamics Lab TIR Solution

THERMAL EARTH RESOURCE MONITORING INSTRUMENT (THERMI) SIZE WEIGHT & POWER (SWAP) REDUCTION STUDY

Objective: Minimize SWAP and meet L8 performance requirements

- We have **openly shared our Smallsat imaging solutions with the community** – the other 5 Teams have not been nearly as transparent
  - Presentations of SST-US VNIR/SWIR and SDL TIR imagers at JACIE 2015
  - Presentation of SDLs THERMI study details at SPIE (following slides)
  - Publication of SDLs THERMI details in forthcoming SPIE paper (ref. below)

Thermal Earth Resource Monitoring Instrument (THERMI) size, weight and power reduction

T. Newswander, Z. Bergen, J. Hancock, S. Hansen, A. Shumway, J. Stauder, D. Williams

11 Aug 2015 11:40 AM - 12:00 PM | Part of SPIE Optical Engineering + Applications

'Quad' charts included to convey level of design detail, analyses, etc.

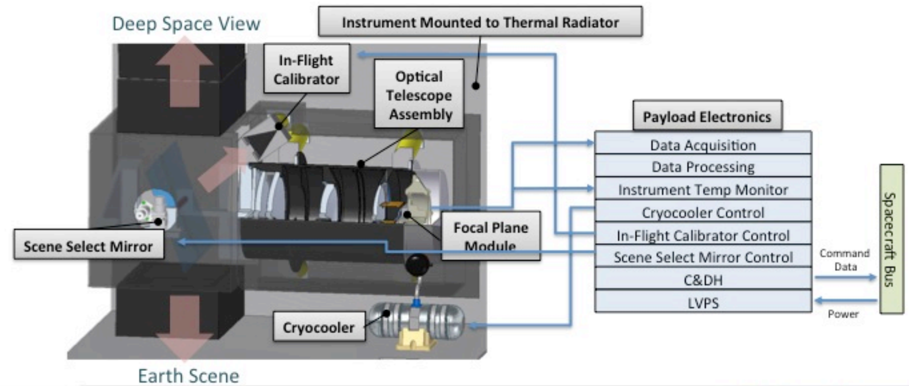
Landsat Heritage Performance Requirements

- Earth resource monitoring
  - Measurement of the land surface temperatures in two long-wave infrared bands
- Requirements include spectral, spatial, and radiometry performance
- Requirements driving Size Weight and Power (SWaP)
  - Radiometry
    - Cryogenic operating temperatures
      - Multiple temperature zones
    - On-board calibration system
    - Straylight rejection
  - Spatial resolution
    - Ground sample distance
    - Relative Edge Response (RER) slope
    - RER edge extent

Objective: Minimize SWAP and meet performance requirements

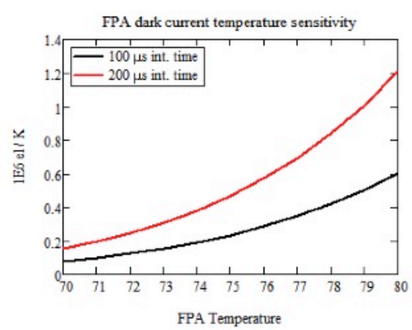
THERMI Overview

- 3 scene select operational modes
  - View Earth
  - View in-flight calibrator
  - View deep space



Focal Plane Module

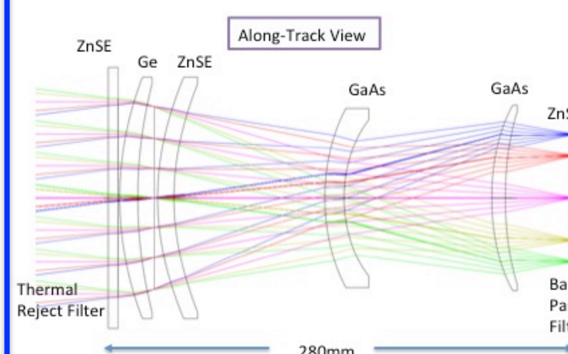
- MCT detector
  - Maximize operating temperature (reduce SWaP)
  - MCT dark current is highly temperature dependent
- Thermal control
  - Minimize temperature to minimize dark current
  - Stabilize temperature to minimize dark offset drift (50 mK stability required for 0.5% radiance uncertainty)
- Format of Four SCAs forming one FPA module
  - Custom development / adaptation of existing MCT designs
- Linear array of ~3080 detectors
  - 25 μm pixel pitch
  - Multiple overlapping sensor chip assemblies

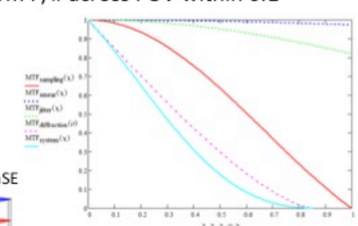


10.8 and 12.0 μm spectral filters bezel-mounted over SCAs

OTA Optical Design

- Aperture 12 cm (F/2.46)
  - Stop positioned to reduce lens size
- Low emissivity high transmittance materials
- Thermal reject filter tilted 1° to reduce ghosting
- Focal length 29.5 cm
- FOV 15°X 2°
- Telecentric within 2 degrees
- Uniform F/# across FOV within 0.1



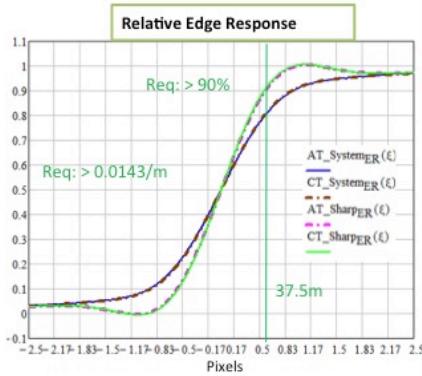


MTF normalized on sampling frequency
- Diffraction
- Detector sampling
- Along track velocity smear
- Jitter

Space Dynamics Laboratory
Utah State University Research Foundation

Edge Response Performance Requirements Met with Sharpening

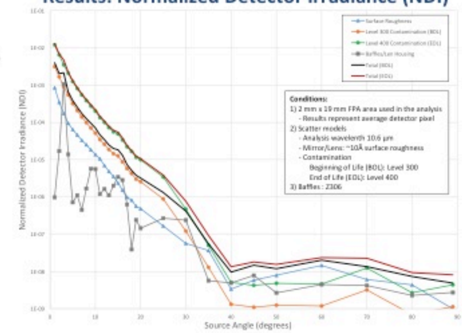
- Relative edge response (RER) analysis includes: diffraction, aberrations, detector sampling, smear along track, jitter
  - Sharpened with low gain 3x3 kernel
- RER requirements are met with sharpening with a slower lens system
  - Overshoot <3% (requirement <5%); Ripple <1% (requirement <5%)
  - SNR reduces 15% - 86%
- Benefit of sharpening: RER requirements require 23.6-cm diameter lens
  - Larger lens requires ~3X mass, ~4X vol. and ~2X power (compared to 12cm lens)



Stray Light Analysis Predicts Low Impact

- Analysis completed in non-sequential Zemax
- Rays traced from simulated point source to detector
  - Collimated beam at 1° to 89°
  - Azimuthal angles of 0°and 90°
- Scatter off of optical element surfaces due to:
  - Surface roughness
  - Particulate contamination
- Scatter off of baffling and structure

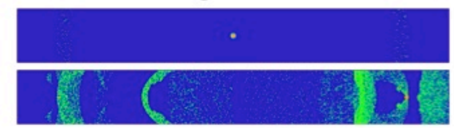
Results: Normalized Detector Irradiance (NDI)



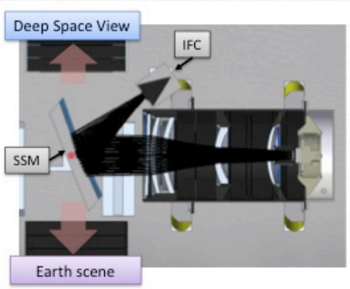
- Predicted stray-light fraction from off-axis earth radiance
  - Beginning of life (BOL) 0.06%
  - End of life (EOL) 0.18%
    - Assumptions
      - Off-axis scatter from entire visible earth (64.2° half angle)
      - Scene temperature: Target 300 K; Off-axis 330K

Results: Ghost Analysis (log plot)

- Ghost magnitude <0.001%



In-Flight Calibration System



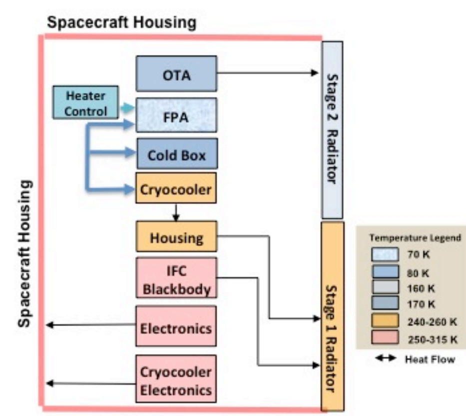
- 2-sided Scene Select Mirror (SSM)
  - Front side flat for normal operation
  - Powered back side mirror reduces IFC from 25 cm diameter to 8 X 1.5 cm rectangular slit
- In-Flight Calibrator (IFC)
  - Hg & Ga phase-change cells provide absolute temperature calibration standards
- Absolute radiometric uncertainty < 2% (260 K to 330 K)
  - Radiance transfer from high-fidelity (NIST traceable) laboratory blackbody is REQUIRED

Concept of Operation

- **Deep space viewed once per orbit to update dark offset correction**
- **Calibration source viewed at longer interval to update calibration of individual detector elements**

Thermal Management Overview

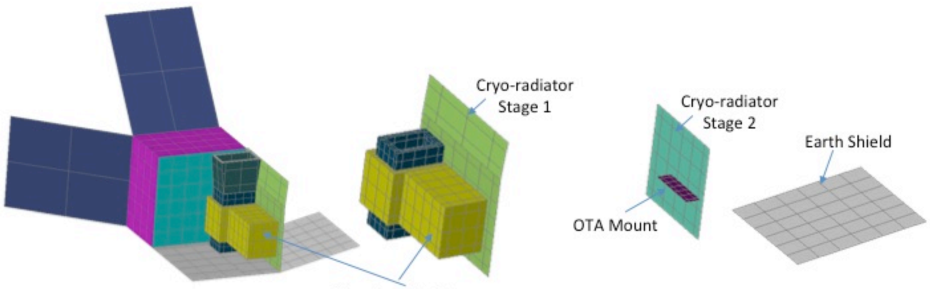
- **OTA**
  - Cooled to <170 K with passive cold radiator
- **FPA**
  - Active cooling with compact pulse-tube cryocooler to 70 K +/- 50 mK
  - Trim heater control
- **Cold Box**
  - Cryocooler cooled to <80 K
- **Mini Pulse Tube Cryocooler**
  - Coldhead temperature 68 K
  - Lift 1.67 W
- **Housing**
  - Cryocooler heat reject <260 K
- **In Flight Calibrator (IFC)**
  - Controlled at 260 K and 310 K
- **Electronics**
  - Temperatures ~ 290 K, stabilized as required
  - Heat rejected to spacecraft radiators



Thermal Analysis

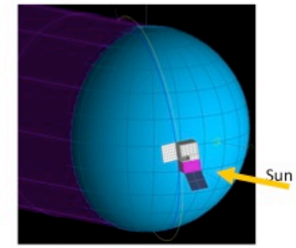
- Two-stage cryo-radiator
  - Stage 1 rejects housing heat loads including cryocooler reject power
  - Stage 2 rejects OTA heat loads
  - Stages mounted with thermal isolating structure
- Use Z93 paint and Vapor Deposited Aluminum (VDA)

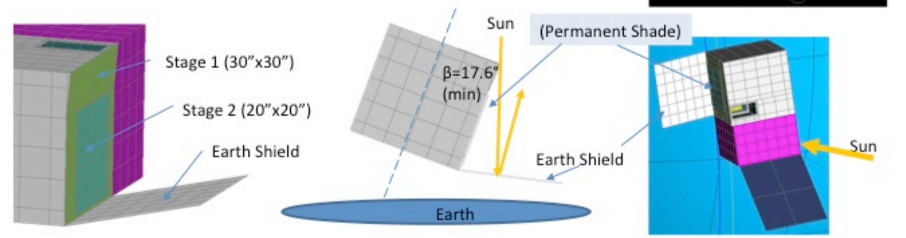
Component	Heat Origin	Heat Rejection Panel	Nominal (W)	Margined (W)
Cryocooler Reject	Elect	Cryo-Radiator Stage 1	19.73	23.68
FPA Tape Cable at SS Housing	Parasitic	Cryo-Radiator Stage 1	0.016	0.02
IFC (Phase Change)	Elect	Cryo-Radiator Stage 1	7.50	9.00
Mirror Motor	Elect	Cryo-Radiator Stage 1	5.80	6.96
OTA Heat Load	Parasitic/ Elect	Cryo-Radiator Stage 2	1.74	2.09
Cryocooler Compressor	Elect	Nadir Panel	29.60	35.52



Cryo-Radiator Earth Shield Design

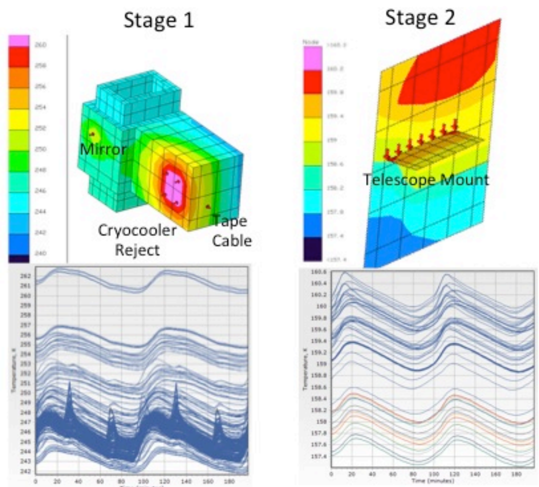
- Earth shield
  - Protects Stage 1 and Stage 2 from significant view of earth
  - Minimum beta angle determines canted angle to specularly reflect sunlight away from cryo-radiator





Cryo-Radiator Thermal Predictions

- Stage 1 required to maintain SS housing to bulk-average temperature <260 K
  - Stage 1 maintains the housing average temperature ~250 K
- Stage 2 required to maintain telescope <170 K
  - Telescope mount base ~160 K under margined loads



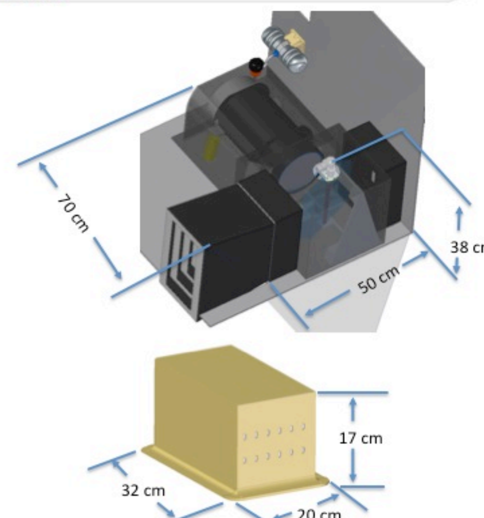
Reductions in SWaP allow THERMI to Fit on a Small Satellite Bus

Mass with Margin		
Payload Electronics	13.1	kg
OTA	8.3	kg
In Flight Calibrator	6.5	kg
Thermal Management	3.8	kg
Covers and Baffles	6.5	kg
Housing and Mounts	18.6	kg
Total	**57**	**kg**

Power with Efficiencies and Margin		
Payload Electronics	32	W
Thermal Management	76	W
In Flight Calibrator	15	W
Total	123	W

SSTL-300 Small Satellite Payload Limits		
Power	140	W
Mass	300	kg
Volume	60 x 70 x 97	cm

*SSTL-150 customized for additional power



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Summary Thoughts

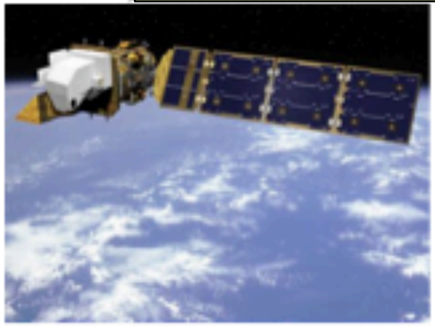
- ***"Smallsat technology has progressed far enough (that) … there is no technical reason why smallsats can't equal the performance and reliability of traditional satellites" …*** observation by Dr. Bryant Cramer (New Millennium Prog Mgr)
- ***"Why are we only building and launching IBM 360 mainframe computer equivalents in an era of laptops, IPAD's and smart phones?"*** observation by Prof Samuel Goward (UMD)
- **IMHO, a smallsat solution should be embraced immediately as an *augmentation* to Landsat 8 and 9**
  - adding such a mission **would yield more frequent coverage** and **serve as relatively low-cost insurance against a crippling data gap**
  - if shown to provide acceptable performance, as we expect, **smallsat solutions should become the new norm for sustained land imaging**
- **Smallsat potential for reliable ET retrievals is high;** the predominant limitations are out dated perceptions and politics

SMALLSAT SOLUTIONS CAN PROVIDE SCIENTIFICALLY VALID DATA RIGHT NOW!

SPACENEWS

The Rime of the Ancient (Land) Mariner

By Samuel N. Goward, Darrel L. Williams | Apr. 1, 2013



Landsat 8. Credit: Orbital Sciences artist's concept

The March 4 *SpaceNews* had a good editorial on the Landsat program ["Enjoy Landsat 8 — While It Lasts," page 18]. However, for those uninitiated in Landsat affairs, it was rather incomplete.

Welcome to a sad tale of many twists and turns told by two ancient Landsat mariners. We are still not certain who shot the Landsat albatross (several names come to mind) but we have had bad luck ever since. Continuation of Landsat past version 8 is only the most recent turn.